Inverse-Inverse Dynamics Simulation of Musculo-Skeletal Systems

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Inverse-inverse dynamics simulation of musculo-skeletal systems

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Introduction

Like all mechanical simulation, multibody analysis of the musculo-skeletal system is essentially a matter of determining unknown output, the dependent variables, from assumed input, the independent variables. The choice of input and output causes the simulation to fall into either of two categories known respectively as inverse dynamics and forward dynamics. In inverse dynamics, muscle and joint forces are computed based on given external loading and motion, i.e., the joint and muscle forces are the dependent variables. In forward dynamics, the situation is the opposite.

A superficial investigation may indicate that inverse dynamics holds some practical advantages over forward dynamics because the inverse dynamics input (IDI) is easier to record than individual muscle forces (the input of forward dynamics). However, many practical movements also involve IDI that is difficult to measure or changes with the working conditions. In bicycling, for instance, the rider at each instant can choose foot angles and pedal forces independently of crank position, and this choice is likely to change if a working condition, for instance the cadence, is changed. Thus, it may appear that inverse dynamics cannot be applied to cases involving unknown or changing IDI.

In forward dynamics, the equivalent problem of unknown muscle forces is solved by formulating an optimum control problem [1], i.e., find the forces that provide the desired motion and fulfil some optimality criterion. The same idea applied to inverse dynamics entails an optimization of the unknown IDI, effectively creating an inverse-inverse algorithm. The two approaches differ only in the choice of variables in the optimization problem, and the best approach to a given problem depends on the expected difficulty of the two optimization problems. In this work, we investigate how the inverse-inverse algorithm can be used to handle kinematic indeterminacy as exemplified by bicycling.

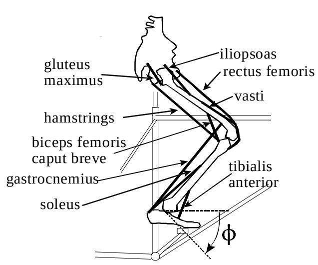

Fig. 1:Model of bicycling leg with nine muscles.

Methods

The model of bicycling comprises two legs, each driven by nine muscles as shown in Fig. 1. Antropometric dimensions are compiled from the literature and adjusted to approximately fit a person of height 1.82 m and 81 kg.

The software is organised into an analysis part wrapped in a general optimization algorithm. The analysis part contains a min/max solver that determines the force in each muscle as described in detail in [2].

The unknown IDI of the problem is the angles of the feet, $\phi(t)$, and the crank torque, $M(t)$, where t is time. We shall set both $\phi(t)$ and $M(t)$ to vary sinusoidally, such that the amplitudes, offsets, and phase shifts are used as optimization parameters. $M(t)$ initially has minimum value zero at the top and bottom dead centres, and $\phi(t)$ has amplitude zero, i.e., starts as a constant function. The initial data is illustrated by the dashed lines in Fig. 2.

The model is then subjected to an optimization that attempts to maximize the metabolic efficiency of the process while maintaining average power output of 200 W. The metabolic efficiency of concentric and eccentric muscle work is assumed to be 25% and -125% respectively. This means that the maximum attainable metabolic efficiency for the total system is 25%. This is an ideal situation that arises when no muscles perform negative work and when all elastic energy stored in tendons is converted to useful mechanical output.

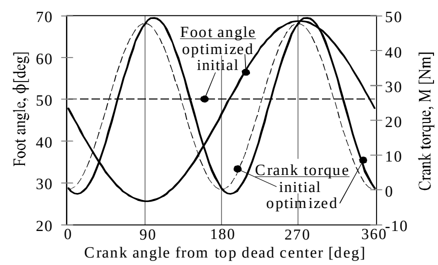

Fig. 2: Optimized foot angle and crank torque.

Results

The optimization increases the simulated metabolic efficiency from 21.9% to 24.8%, indicating that very little energy is lost in negative muscle work and tendon elasticity. The solid lines of Fig. 2 show the angle of the foot and the crank torque after optimization. These curves are consistent with typical bicycle data found in the literature, e.g. [3].

Discussion and conclusions

It appears that the inverse-inverse algorithm is capable of solving kinematically indeterminate problems of the kind that would normally be deemed suitable for optimum-control-based forward dynamics algorithms. In addition, the process is computationally fast with a computing time of non-optimized code of the order of 30 minutes on a personal computer. This is partly due to the smooth nature of the independent parameters that constitute the IDI variables, and partly due to the efficient solution of the muscle recruitment problem [2].

Implementation for general purposes is in progress.

References

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